Thresholds of Adverse Effect of Macroalgae on Estuarine Intertidal Flats:

Findings of Studies Supporting an Estuarine Macroalgal Nutrient Numeric Endpoint

A Webinar Sponsored By The California Water Quality Monitoring Collaboration Network

October 31, 2012
9:30-11:30
State Water Resources Control Board is Developing Nutrient Objectives

• Freshwater (lakes and streams)
  – Work initiated in 2000
  – Technical work complete
  – Policy under development

• Estuaries
  – Work initiated in 2008
  – Scientific studies are being conducted to support decision-making

• Today’s presentation presents a component of science supporting nutrient objective development in estuaries
Overview of Presentations

- State Water Board’s conceptual approach to nutrient objectives (Martha Sutula, SCCWRP)
  - Need for numeric endpoints for macroalgae
- Why macroalgae? (Peggy Fong, UCLA)
  - Ecology of macroalgal blooms in estuaries
- Effects of macroalgal blooms on benthic infauna—results of field experiments (Lauri Green, Harbor Branch Oceanographic Institute)
- Effects of macroalgal blooms on benthic habitat quality—results of a sediment profile imagery survey (Martha Sutula, SCCWRP)
- Synthesis and next steps (Martha Sutula, SCCWRP)
Approach to Setting Nutrient Objectives Distinct From That Used For Traditional Contaminants

- Nutrients are required to support life
  - How much is too much?

- Toxicity rarely endpoint of interest
  - Effects occur at much lower levels

- Using ambient nutrients to diagnose effects can often give a false-negative or false-positive
  - Need a different approach
Tenets of California’s Approach to Nutrient Objectives

• Narrative objective, with numeric guidance
  – Guidance coined as “Nutrient Numeric Endpoint or NNE”

• Diagnosis based on response indicators = NNE assessment framework
  – Assessing eutrophication et al. adverse effects of nutrients
  – Multiple lines of evidence for more robust diagnosis

• Models to link response indicators to nutrients et al. factors (e.g. hydrology, climate, etc.)
  – Can be empirical or dynamic simulation models
Ecological Responses Are More Strongly Linked to Beneficial Uses Than Nutrients Alone

A. Driver/Stressor
- Increased Nutrient or Organic Matter Loading

B. Ecological Response Indicators
- Change in Primary Producer Biomass and/or Community Structure
- Change in Sediment and Water Column Physiochemical Parameters and Rates of Metabolism
- Change in Biomass and/or Community Structure of Secondary Consumers (e.g. Zooplankton, benthic macroinvertebrates, etc.)

C. Risk Cofactors
- residence time
- Climate
- sediment load
- dilution
- stratification
- geomorphology
- top-down grazing
- denitrification

D. Management Endpoints of Concern
- Ecological Endpoints
  - Fish
    - ↓ Food
  - Birds
    - ↑ Stress
    - ↑ Mortality
  - Invertebrates
- Human Endpoints
  - ↓ Aesthetics
  - ↑ Illness
  - ↑ Odor/Taste

E. BU Impairment
- Migr
- Rare
- Habitat
- Spwn
- Comm
- Aqua
- Shell
- Rec1
- Rec2
- Aqua
- Shell
Application of the NNE In Streams: Example of Endpoints for Benthic Algal Biomass

Benthic Algal Biomass
+ pH
+ Dissolved Oxygen

<table>
<thead>
<tr>
<th>Benthic Algal Biomass Thresholds (mg chl a m⁻²)</th>
<th>Beneficial Use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COLD</td>
</tr>
<tr>
<td>BURC I/II</td>
<td>100</td>
</tr>
<tr>
<td>BURC II/III</td>
<td>150</td>
</tr>
</tbody>
</table>

Defined
Assess Eutrophication, Manage Nutrients

Use models to convert response thresholds into nutrient goals

—Key to how we protect beneficial uses

Increasing Precision, Accuracy, and Utility for Scenario Analysis

Empirical Models

Simple Box or Spreadsheet Models

Calibrated Numerical Models

Increasing Data Requirements, Cost
Conceptually Application of NNE Same Across Waterbody Type

Indicators, thresholds and appropriate models differ:

- Streams
- Lakes
- Estuaries
Estuarine NNE Workplan: Phasing

- NNE Assessment Framework
  - Phase I
- Load-Response Models
  - Phase II

Estuarine NNE
Evaluation of Candidate Estuarine NNE Indicators

• Evaluated candidate indicators vis-à-vis review criteria
  – Clear link to beneficial uses
  – Can build model to link to nutrients
  – Scientifically sound & practical measure
  – Reliably use to diagnose eutrophication (signal: noise acceptable)

• Reviewed studies to establish thresholds
  – Identifies data gaps and next steps

• Chapter authored by Fong, Green and Kennison on macroalgae
# Estuarine Classification

<table>
<thead>
<tr>
<th>Geoform</th>
<th>Tidal Regime</th>
<th>No.</th>
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</thead>
<tbody>
<tr>
<td>Enclosed Bay</td>
<td>Perennial</td>
<td>30</td>
</tr>
<tr>
<td>Lagoon</td>
<td>Perennial</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Intermittent</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>Ephemeral</td>
<td>46</td>
</tr>
<tr>
<td>River mouth</td>
<td>Perennial</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Intermittent</td>
<td>270</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>405</td>
</tr>
</tbody>
</table>
Habitat Types Considered in Estuarine NNE Framework

Include:
- Intertidal flats
- Seagrass et al. submerged aquatic vegetation
- Unvegetated subtidal

Exclude:
- Emergent marsh
## Recommended Indicators

<table>
<thead>
<tr>
<th>All Subtidal</th>
<th>Intertidal Flats and Shallow Subtidal</th>
<th>Seagrass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved oxygen</td>
<td>Macroalgal biomass/cover</td>
<td>Phytoplankton Biomass</td>
</tr>
<tr>
<td>Phytoplankton Biomass and Assemblage</td>
<td></td>
<td>Macroalgal Biomass and Cover</td>
</tr>
<tr>
<td>HAB cell counts &amp; toxin conc.</td>
<td></td>
<td>Light attenuation</td>
</tr>
<tr>
<td>-- Cyanobacteria</td>
<td></td>
<td>Epiphyte load</td>
</tr>
<tr>
<td>Macroalgal biomass/cover</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Phytoplankton](image1.png)

![Macroalgae](image2.png)

![Epiphytes on Seagrass](image3.png)
In Bar-Built Estuaries, Inlet Status Controls Dominant Primary Producers

Benthic diatoms and macroalgae on intertidal flat in “open” state

Floating macroalgae, submerged aquatic vegetation & phytoplankton in “closed” state
NNE Assessment Framework: Simplified Classification

- Enclosed Bays
- Open State
- Closed State
- Bar Built Estuaries
  - Lagoonal Estuaries
  - River Mouth Estuaries
• Same Indicators in “open” versus “closed” estuaries
• But ....different assessment frameworks
  — Thresholds
  — Guidance for how to measure and how to use data to make an assessment
Estuarine NNE Assessment Framework: Primary Producers

Open Estuaries
- Unvegetated Subtidal
- Seagrass
- Intertidal

Closed Estuaries
- All Subtidal

Phytoplankton NNE
- Macroalgae NNE

All
- Subtidal

Closed
- Estuaries
Estuarine NNE Assessment Framework: Primary Producers

Open Estuaries
- Unvegetated Subtidal
- Seagrass
- Intertidal

Phytoplankton NNE

Macroalgae NNE

Closed Estuaries
- All Subtidal
Studies Supporting Macroalgal Numeric Endpoints

“Open Estuaries”

• Field experiments and survey of effects of macroalgae on intertidal and shallow subtidal habitat- Complete

• Field experiments and survey of effects of macroalgae on seagrass habitats- Work in progress

Closed Estuaries

• Field survey documenting natural background abundances of macroalgae and phytoplankton in “closed” estuaries- Begin in 2013
Defining Terms: Thresholds vs. Benchmarks

- Reference Envelope
- No effect level (benchmark)
- Resistance Threshold
- Adverse effect level (benchmark)
- Exhaustion Threshold

(Cuffney et al. 2010)
Overview of Presentations

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  - A Primer on ecology of macroalgal blooms in estuaries

- Effects of macroalgal blooms on benthic infauna—results of field experiments (Lauri Green, Harbor Branch Oceanographic Institute)

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- Synthesis and next steps (Martha Sutula, SCCWRP)
Basic Ecology of Ephemeral Macroalgae

• A little taxonomy and ecology
  - macroalgae come in 3 flavors:
    - **green, red, and brown**
    - support vital ecological functions in all aquatic systems

• Macroalgae have extremely diverse morphologies:
  - blooms species have simple thalli (body/form)
  - often undergo changes in habitat usage through different life stages
Macroalgae are Found in Many Estuarine Habitat Types

- Surface of mudflats (intertidal)
- As epiphytes on seagrass (shallow subtidal)
- Floating mats (deeper brackish lakes and deepwater enclosed bays)
Rapid nutrient uptake abilities produce rapid growth

Kennison, Kamer, and Fong 2011
Journal of Phycology 47: 483-494
High nitrogen supply enhances tolerance to extremes: nutrients ameliorate negative effects of low salinity

Kamer and Fong 2001
Marine Ecology Progress Series 218: 87-93
Result: ubiquitous in shallow estuaries, prolific in nutrient-rich estuaries
Excessive Nutrients Causes Shifts in Dominant Primary Producers

Increased N-loading shifts from microphytobenthos, phytoplankton, or seagrass to macroalgae to cyanobacteria domination.

Fong, Zedler and Donohoe 1993
Limnology and Oceanography 38: 906-923
Conceptual Model of Effects of Macroalgae

Nutrient load

- Light
- N Loss
- O₂ respiration
- O₂ respiration
- O₂ respiration

- N cycling and loss
- Anoxia (Sulfate Reduction)
- Anoxia (Sulfate Reduction)
- Anoxia (Sulfate Reduction)

Low Organic Matter Burial

Minimally Disturbed

Increased Nutrient Loading

High Organic Matter Burial

Affected by Eutrophication
Effects on Management Endpoints of Concern

- Poor surface water quality (strong diel DO fluctuations and hypoxia, increased bacterial growth)
- Poor benthic habitat quality (Increased sediment organic matter accumulation, sediment anoxia, increased pore water sulfide, ammonia, etc.)
- Changes in food web (shifts in food supply for upper trophic levels)
- Loss of critical habitat for fisheries, birds, esp. T&E species

<table>
<thead>
<tr>
<th>Ecological Endpoints</th>
<th>Fish</th>
<th>Birds</th>
<th>Invertebrates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>↓ Food</td>
<td>↑ Stress</td>
<td>↑ Mortality</td>
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</tbody>
</table>

Change in Sediment and Water Column Physiochemical Parameters and Rates of Metabolism

Change in Primary Producer Biomass and/or Community Structure

Change in Biomass and/or Community Structure of Secondary Consumers (e.g. Zooplankton, benthic macroinvertebrates, etc.)
Lots of Literature on Effects of Macroalgae, But..

• Little literature characterizing the “dose-response” that would be valuable for endpoint selection
Does Macroalgae Have A Predictive Relationship with Nutrients?

• Yes - best example is Waquoit Bay (MA)
  – Total nutrient loads predict algal biomass in 3 sub-basins with differing loads
  – But the relationship is complex (easiest where river sources are dominant)

• Co-factors play a large role in regulating response to nutrients
Temporal and Spatial Variability of Blooms in Estuaries Can be High

An example from Carpinteria Marsh

More algae near river inflow

In some years, blooms coincide with winter fertilization of strawberry fields
Abundance is Typically Measured Using Transects To Estimate Biomass and %Cover
A Primer On Macroalgae: Summary

- Macroalgae are a natural and beneficial part of estuaries
- Flavors of macroalgae – red, brown and green
- Rapid uptake abilities, plasticity in growth form, combined with tolerance to environmental extremes makes them prolific in anthropogenically disturbed systems
- Macroalgae outcompete other primary producers as nutrient loads increase
- Well documented relationship with nutrient loads
- Spatially and temporally variable
  - Typically measured by estimating biomass and % cover
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- Synthesis and next steps (Martha Sutula)
Field Experiments-Overview

• Why do we focus on macrobenthos as management endpoint of concern?

• What information can previous studies provide?
  – Green (2011) experiments in Mugu Lagoon

• NNE field experiments
  – Methods
  – Results
  – Relevance to synthesis of information on thresholds
Why Study the Response of Infauna and Epifauna?

Important to food web support & Biogeochemical cycling
Importance of Macrofaunal Functional Groups

Suspension and Surface Deposit Feeders, Herbivores:

- Graze on phytoplankton, microphytobenthos, macroalgae, detritus == bottom of the food chain
- Important prey for birds, fish and crustaceans
- Burrowing and irrigating increase oxygen penetration and enhance nitrogen removal
Surface Deposit Feeders Are More Accessible to Birds & Fish Than Subsurface Deposit Feeders
Macrobenthos Are Part of Feedback Loop that Control Depth of Oxygen Penetration in Sediments

- Diverse macrobenthos mix sediment, increasing depth of oxygen penetration
- High organic matter loading reduces sediment redox potential
- Sulfate reduction shallows, causing high pore water sulfide
- Sulfide is toxic to many benthic organisms
Previous Studies

• Previous studies showed a negative effect of macroalgae on benthic invertebrates (e.g. Hull 1987).
  – Methods tended to be a single application of macroalgae (Hull 1987), a single treatment (Cummins et al 2004) or field surveys (Jones and Pinn 2006).
  – Effects based on multiple treatments and continuous application (and monitored by frequent sampling) were lacking.

• Green (2011) first field experiment with tight control on dose and duration
Initial Experiment Consisted of 3 Treatments Maintained for 8 Weeks (Green 2011)

~0-60 g dw m$^{-2}$  ~190 g dw m$^{-2}$  510 g dw m$^{-2}$

Mugu Lagoon
Sampling Protocol

• Sampled infauna initially, then every two weeks for 8 weeks
  – Documented change in macrobenthic species diversity and abundance

• Week 6-8 deployed “peepers” to measure pore water sulfide and ammonium
Findings:

- 190 g treatment: significant negative effect on diversity, decrease in surface deposit feeders
- Level associated with high pore water sulfide
- Control had no observed effect
Estuaries Differ With Respect to:

- Climate
- Hydrology
- Sediment organic matter and grain size
- Benthic community
Are Benchmarks the Same Despite Differences Between Estuaries (and the Sites Within Estuaries)?
Bodega Bay Has Higher Sand Content, Lower Organic Matter than Upper Newport Bay
Broader Treatment Range, Similar Sampling Protocol to Earlier Experiment

Sampled infauna & epifauna initially and every two weeks for eight weeks.
Surface Deposit Feeders Declined at 110-120 g dw m$^{-2}$
Similar Patterns Were Found With Diversity, Herbivores and Suspension Feeders
What makes UNB$_2$ less responsive to macroalgae?

One explanation is the composition of the benthic community.
Subsurface Deposit Feeders Increased at 110 g dw m$^{-2}$ or Greater
Total Infauna Increased at Some Sites, Due to Increase in Subsurface Deposit Feeders
Study Establishes Lowest Observed Effect Benchmark

Macroalgal Biomass (g dw m$^{-2}$)
Summary of Field Experiment Findings

• Strong negative effects on infauna and epifauna at ~100-120 g dw m\(^{-2}\)

• Rapid response by benthic community within 2-4 weeks of treatment

• Similar benchmark for two very different estuaries

• High abundances of subsurface deposit feeders (UNB\(_2\)) may indicate a disturbed state not strongly affected by added eutrophic stress
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- Synthesis and next steps (Martha Sutula)
How Do We Extrapolate These Findings Across Estuaries?

- Depth to apparent redox potential discontinuity (aRPD)

Sediment Profile Imagery (Rhoads and Cande, 1971)
Sediment Profile Imagery Survey: Approach

- Survey of 16 sites in 8 estuaries
- At each site, measured suite of parameters in 20 plots along a transect
  - Macroalgal biomass and % cover
  - Sediment %OC, %N, % fines
  - aRDP from sediment profile imagery

Sutula et al. (submitted to Estuaries and Coasts)
Eight Estuaries Captured Diversity of California Estuaries
Data Illustrate That Lots of Factors Control aRDP, But That Macroalgae At Some Point Override Other Factors

Symbol shape represents different estuary

- No Algae
- Red Algae
- Green Algae
Used Statistical Modeling Approaches Can Identify Two Types of Thresholds

- Classification and Regression Tree Analysis (CART) to identify “step thresholds” = reference/non-reference population
- Piecewise regression to identify slope thresholds = exhaustion threshold
Macroalgal Biomass of 2-16 g dw m$^{-2}$ Defined as a Reference Envelope Based on aRDP

![Graph showing biomass and aRDP values with cut point and 95% C.I.]

Cut Value = 14.1 (2.7-16.2)
0.4-0.5% OC Defined as a Reference Envelope Based on aRPD

Cut Value = 0.46 (0.39-0.53)
Biomass of 175-190 g dw m\(^{-2}\), 1.1\%OC Defined as a Exhaustion Threshold Based on Site-Averaged Data

<table>
<thead>
<tr>
<th>Fit method</th>
<th>Y-intercept</th>
<th>Slope</th>
<th>X-Intercept Parameter Estimates (Bootstrap 95% C.I.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Median</td>
</tr>
<tr>
<td>Least squares</td>
<td>4.5</td>
<td>-0.013</td>
<td>318.6</td>
</tr>
<tr>
<td>Robust regression</td>
<td>3.9</td>
<td>-0.011</td>
<td>318.0</td>
</tr>
</tbody>
</table>

Slope only (no break) model best fit for Macroalgal Biomass

Slope + break model best fit for Sediment %OC
Study Establishes Reference Envelope and Exhaustion Thresholds for Macroalgae, Supports Pelletier et al (2011) Findings for %OC Thresholds

- Lowest Observed Effect Benchmark: 110-120
- Exhaustion Threshold: 175-190

Legend:
- a Green, Fong and Sutula (in review)
- b Sutula et al. (in review)
Strong Feedback Loop Between Macroalgal Biomass and Sediment Organic Matter Content
% Cover Has No Relationship with aRDP
......But May Have Potential As Screening Variable

< 30% cover, only 5% of plots exceeded a biomass of 14 g dw m\(^{-2}\)
Sediment Profile Imagery Survey: Findings

• Study established reference envelope and exhaustion thresholds for macroalgal biomass and sediment %OC
  — Reference envelope of 2-16 g dw macroalgal biomass m\(^{-2}\) and 0.4-0.5% OC
  — Resistance threshold of 175-190 g dw macroalgal biomass m\(^{-2}\) and 1.1%OC

• Strong relationship between sediment %OC and macroalgae indicative of feedback loop

• No relationship between aRDP and cover, but may be possible to use % cover as a screening tool
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• Synthesis and next steps (Martha Sutula)
Synthesis of Thresholds: NNE Studies Do Not Inform No Effect Level and Resistance Threshold

Ecological Condition

Reference Envelope

No effect level (benchmark)

Resistance Threshold

Lowest Observed Effect Benchmark

Exhaustion Threshold

2-16

110-120

175-190

Macroalgal Biomass (g dw m⁻²)

a Green, Fong and Sutula (in review)

b Sutula et al. (in review)
Can Other Studies Fill In Gaps in Thresholds?

- **Green (2011)** - Field experiment, continuous application
  - High pore water sulfide, severe effects benchmark of 190 g dw m$^{-2}$

- **Bona (2006)** - Field survey with benthic camera, single estuary
  - Loss of Stage III benthic colonizers at 90 d dw m$^{-2}$

- **Cardoso et al. (2004)** - Field experiment, single application
  - No adverse effect at 30 g dw m$^{-2}$

- **Green (2011)** – Field experiment, continuous application
  - Control = algal removal (biomass varied from 0-60 g dw m$^{-2}$)
  - No effect found, but biomass not constant
Other Studies Can Shed Light on Information Gaps, Policy Decision on What to Use

Macroalgal Biomass (g dw m$^{-2}$)

Ecological Condition

Reference Envelope

No effect benchmark

Resistance Threshold

Lowest Observed Effect Benchmark

Exhaustion Threshold

Severe Adverse Effect Benchmark

2-16$^b$

30$^e$

90$^d$

110-120$^a$

175-190$^{b,c}$

a Green, Fong and Sutula (in review)
b Sutula et al. (in review)
c. Green (2011)
e. Cardoso et al. (2004)

No effect benchmark
### Next Steps: Develop Macroalgal Assessment Framework to Support NNE


<table>
<thead>
<tr>
<th>Biomass (g dw m(^{-2}))</th>
<th>&lt;5%</th>
<th>5% to 15%</th>
<th>15% to 25%</th>
<th>25% to 75%</th>
<th>&gt; 75%</th>
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</thead>
<tbody>
<tr>
<td>&gt; 400</td>
<td>Moderate</td>
<td>Low</td>
<td>Very Low</td>
<td>Very Low</td>
<td>Very Low</td>
</tr>
<tr>
<td>130 to 400</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low</td>
<td>Very Low</td>
<td>Very Low</td>
</tr>
<tr>
<td>70 to 130</td>
<td>Good</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>10 to 70</td>
<td>High</td>
<td>Good</td>
<td>Good</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>&lt; 10</td>
<td>High</td>
<td>Good</td>
<td>Good</td>
<td>Moderate</td>
<td>Moderate</td>
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</table>
Co-Authors and Acknowledgements

• Co-authors: Naomi Detenbeck and Giancarlo Cichetti, EPA ORD National Health and Environmental Effects Research Laboratory, Atlantic Ecology Division

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• Taxonomic Quality Assurance: Tony Phillips
References Cited


Sutula, Green, Cichetti, Detenbeck, and Fong (in review). Thresholds of Adverse Effects of Macroalgal Abundance and Sediment Organic Matter on Benthic Habitat Quality in Estuarine Intertidal Flats (http://californiaestuarinenneproject.shutterfly.com/)

Comments? Questions?

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Lauri Green     cnidaria79@gmail.com
Suspension feeders

BOD₁

BOD₂

Suspension feeders m⁻² x 10³

Mat depth (cm)
Herbivores

Mat depth (cm)

Herbivores m$^{-2}$ (x10$^3$)

BOD$_1$

UNB$_1$

BOD$_2$

UNB$_2$
Richness